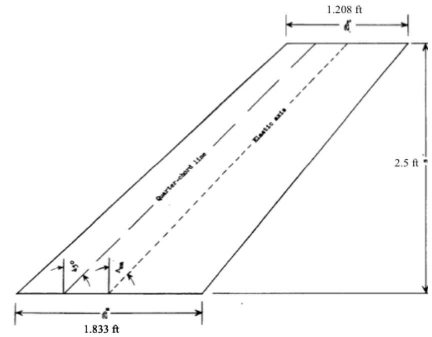
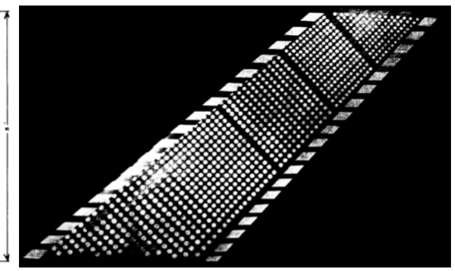
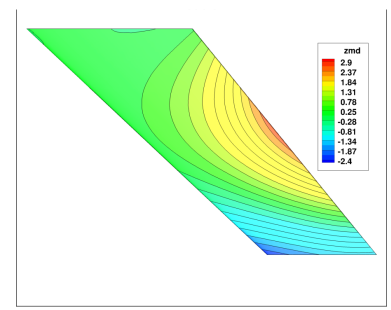
Evaluation of Linear, Inviscid, Viscous, and Reduced-Order Modeling Aeroelastic Solutions of the AGARD 445.6 Wing Using Root Locus Analysis

Walt Silva
Pawel Chwalowski
Boyd Perry, III (Retired)
Aeroelasticity Branch
NASA Langley Research Center







AMS Seminar
NASA Ames
April 14, 2015

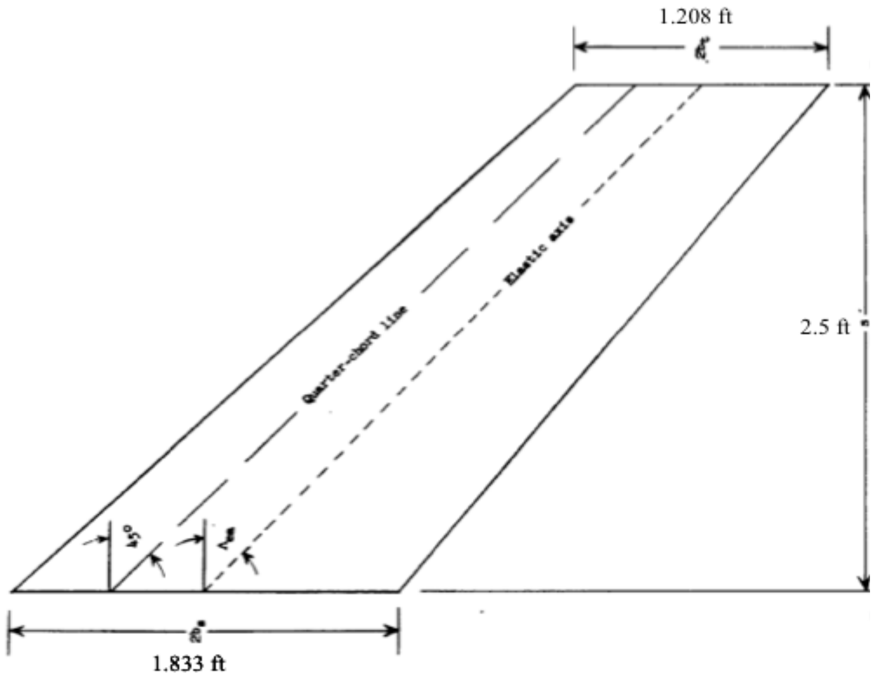
Outline

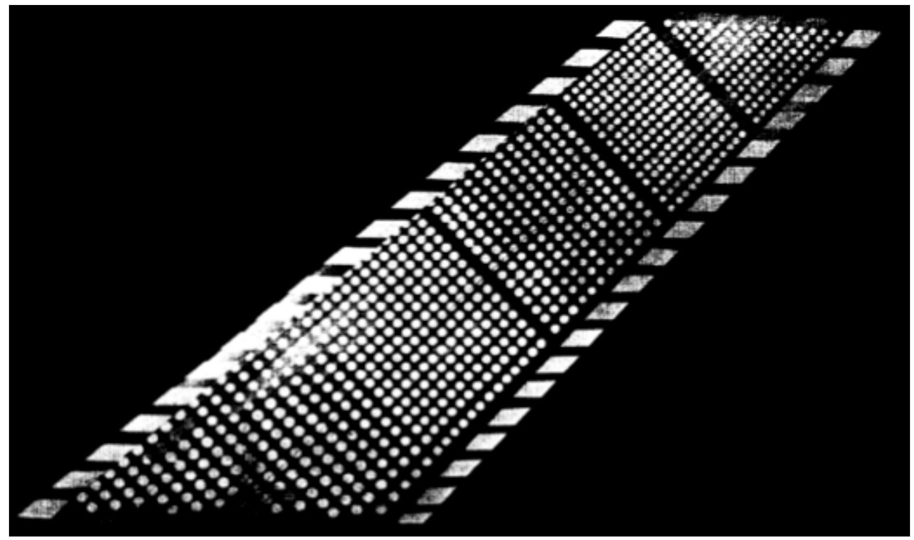
- Background and Motivation
- AGARD 445.6 wing
- Description of Methods
  - CAP-TSD
  - CFL3D
  - FUN3D
  - Reduced-Order Model (ROM)
- Preliminary Discussion
- Early Results (1980's)
- Published Results
- FUN3D/CAP-TSD Results
- Post-Processing of AE Transients
- ROM Root Locus
- Concluding Remarks

Background and Motivation

- Linear AE analyses yield V-g-f plots and/or root locus plots
  - 1986, Gilbert & Silva, X-Wing vehicle analyses indicated static AE instability
- As CFD-based AE analysis developed, results not directly suitable for V-g-f plots or root locus plots (snapshots of transients; stable or unstable)
- Questions:
  - What are we missing by not viewing AE mechanisms using root locus, for example?
  - Are we using linear models as often as possible?
- **Revisit** the standard AGARD 445.6 wing flutter data
- Re-generate linear AE results for AGARD 445.6 wing using CAP-TSD code
- Generate ROMs for AGARD 445.6 wing and related root locus plots
- There are unanswered questions for the AGARD 445.6 wing analyses
- Need to clarify, once and for all, significant misinformation regarding AGARD 445.6 wing
- Concern regarding UQ/V&V for more complicated configurations

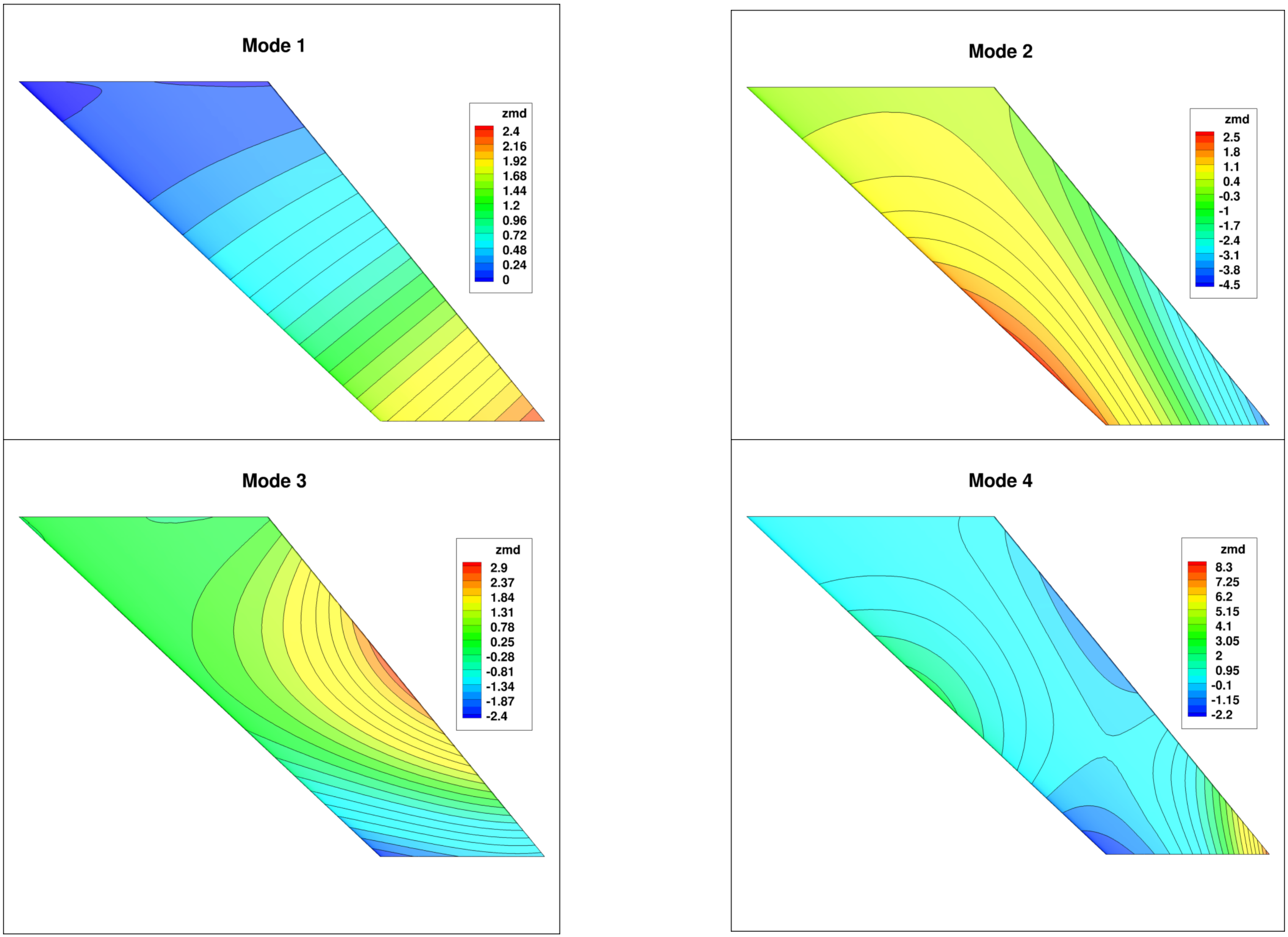
AGARD 445.6 Wing





- Data acquired in the TDT in the 1960's, NASA reports by Dr. E. C. Yates, Jr.
- 45º sweep, 4% thick airfoil (very thin airfoil), data acquired at 0º AOA
- Used significantly (overused? misused?) for CFD code comparisons
- Measured flutter data often misrepresented in literature as "highly nonlinear" flutter boundary, "transonic flutter dip"

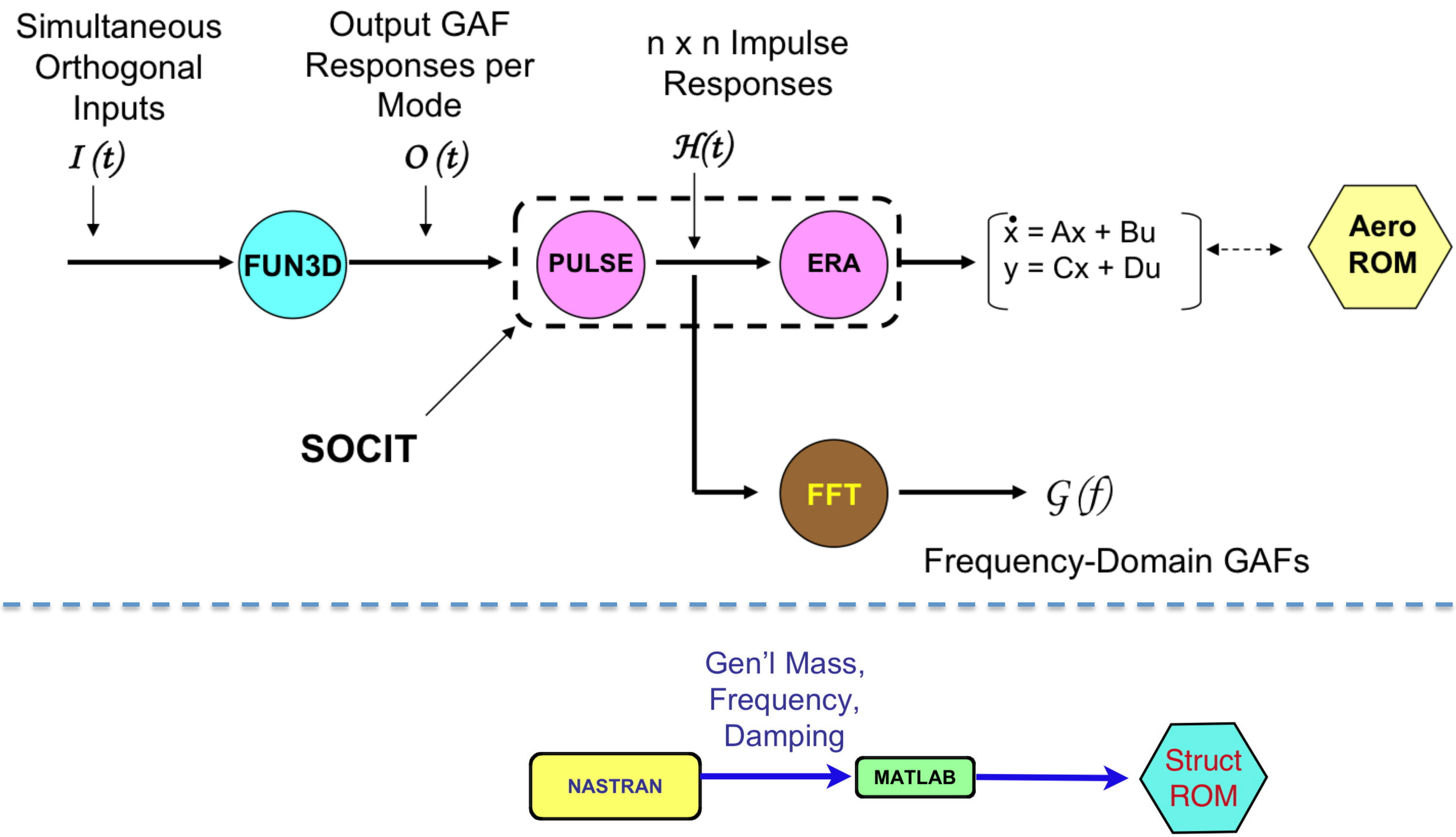
AGARD 445.6 Wing – Mode Shapes



Description of Methods

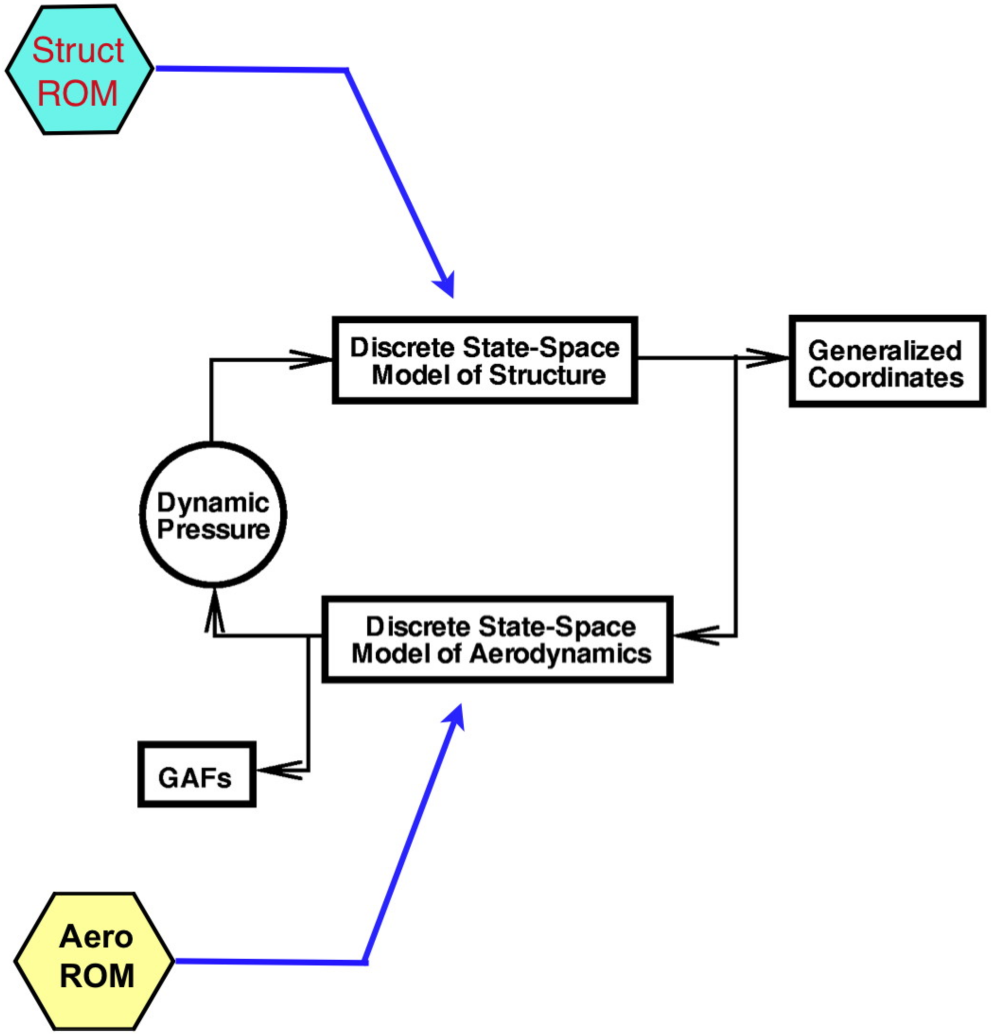
- CAP-TSD (Computational Aeroelasticity Program – Transonic Small Disturbance)
  - Developed at NASA Langley (1980's)
  - Solves the nonlinear TSD equation
  - Inviscid version
  - Linear and nonlinear options
  - **Presenting Linear results**
- FUN3D
  - Developed at NASA Langley
  - RANS
  - Unstructured grid (~4 million grid points)
  - **Presenting Euler and N-S (SA) results**
- CFL3D
  - Developed at NASA Langley
  - RANS
  - Results similar to FUN3D results (Not presented here)

Description of Methods – ROM (1 of 2)



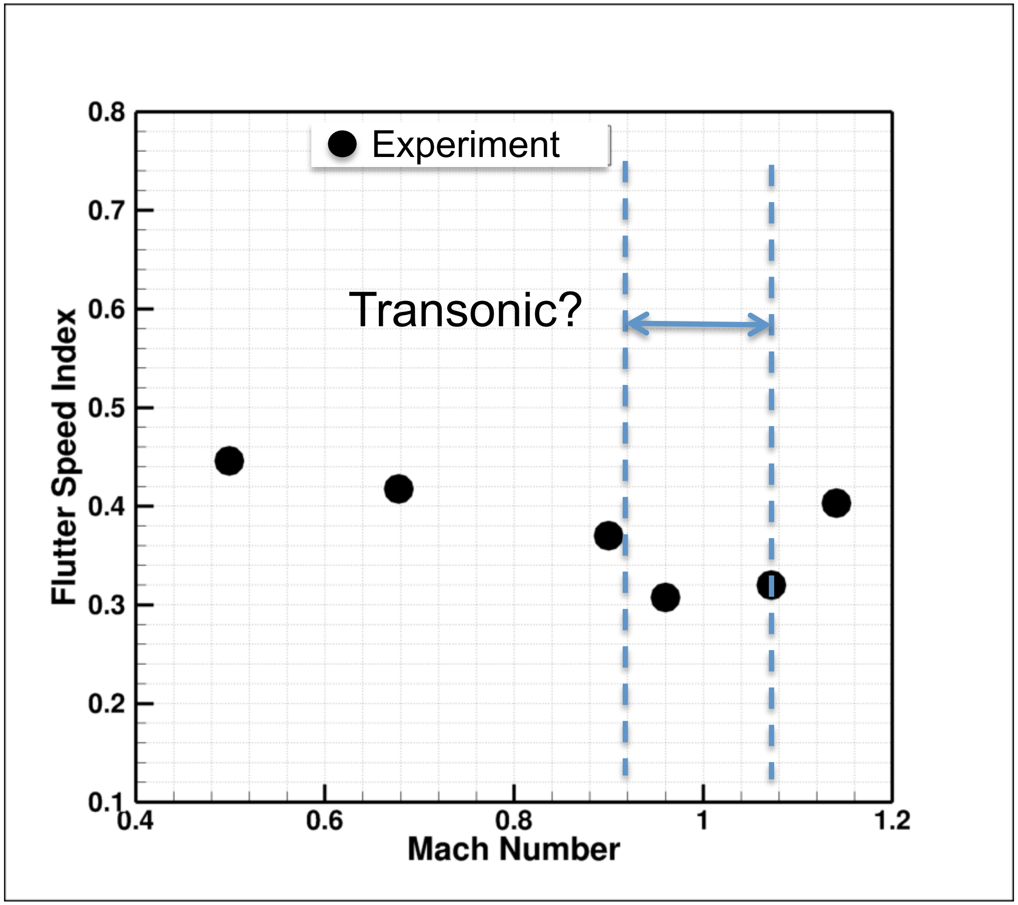
Patent 8,060,350: Method of Performing Computational Aeroelastic Analyses

Description of Methods – ROM (2 of 2)



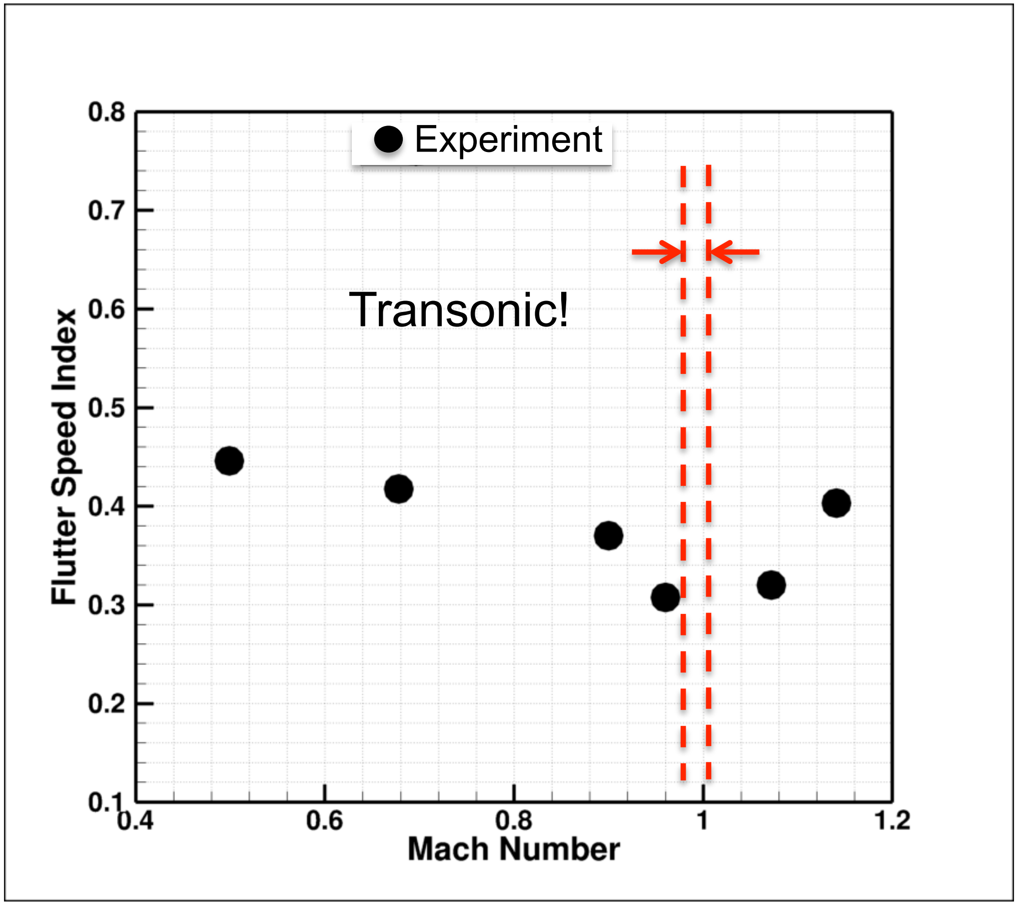
Root Locus Plots f(Q, vel)

Preliminary Discussion – Test Data



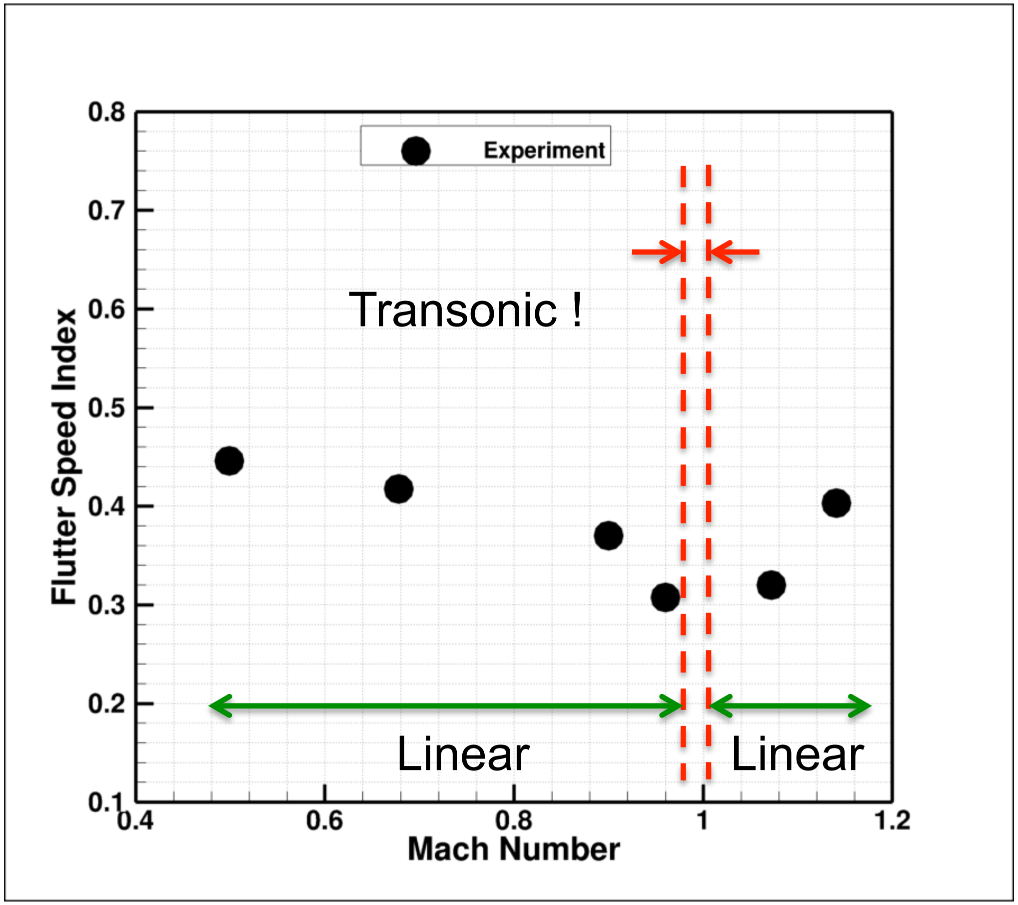
- What are the expected results based on the physics?
- Thin airfoil at zero degrees AOA implies small disturbance
- This implies little, if any, nonlinear (transonic) effects

Preliminary Discussion – Test Data



- What are the expected results based on the physics?
- Thin airfoil at zero degrees AOA implies small disturbance
- This implies little, if any, nonlinear (transonic) effects
- Actually, mixed (transonic) flow starts at M=0.98, ends at sonic flow

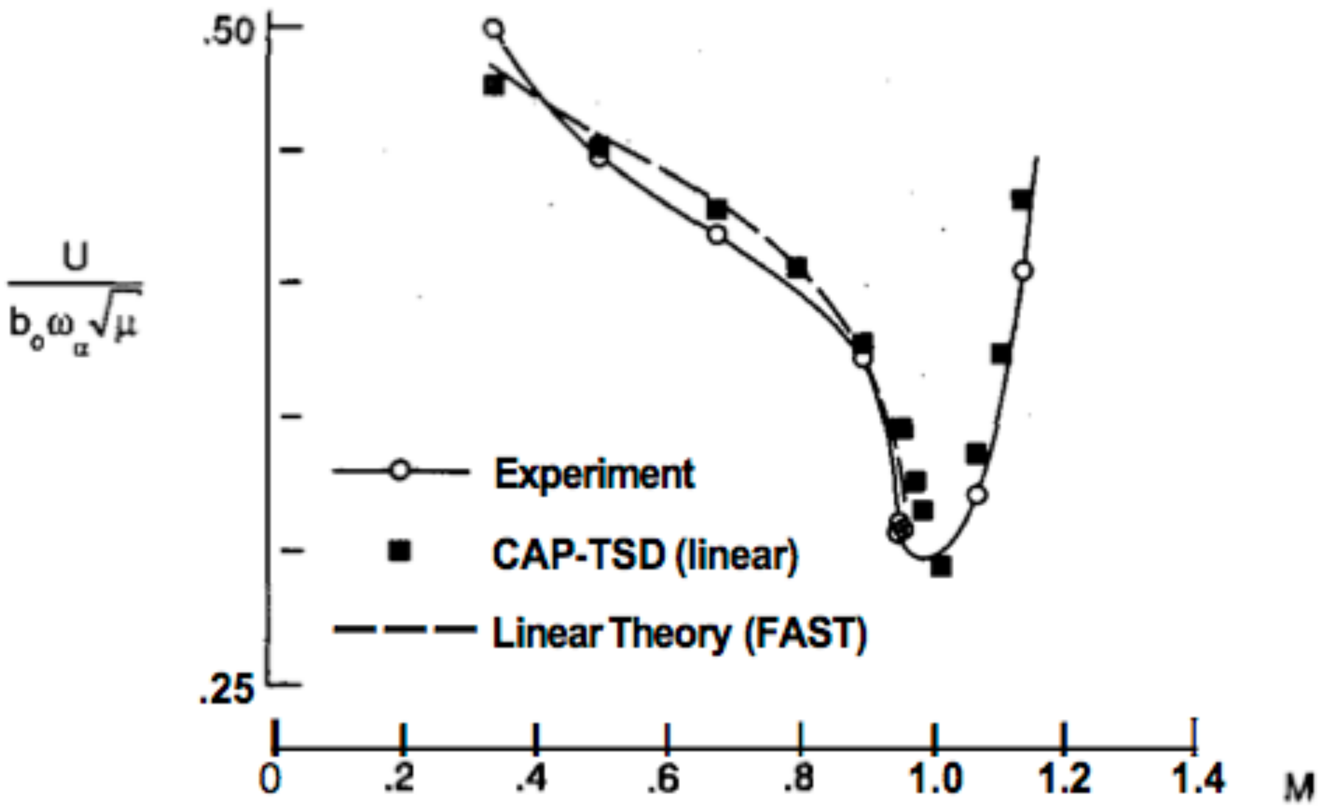
Preliminary Discussion – Test Data



- What are the expected results based on the physics?
- Thin airfoil at zero degrees AOA implies small disturbance
- This implies little, if any, nonlinear (transonic) effects
- Actually, mixed (transonic) flow starts at M=0.98, ends at sonic flow
- Therefore, flow and response before and after transonic region should be linear

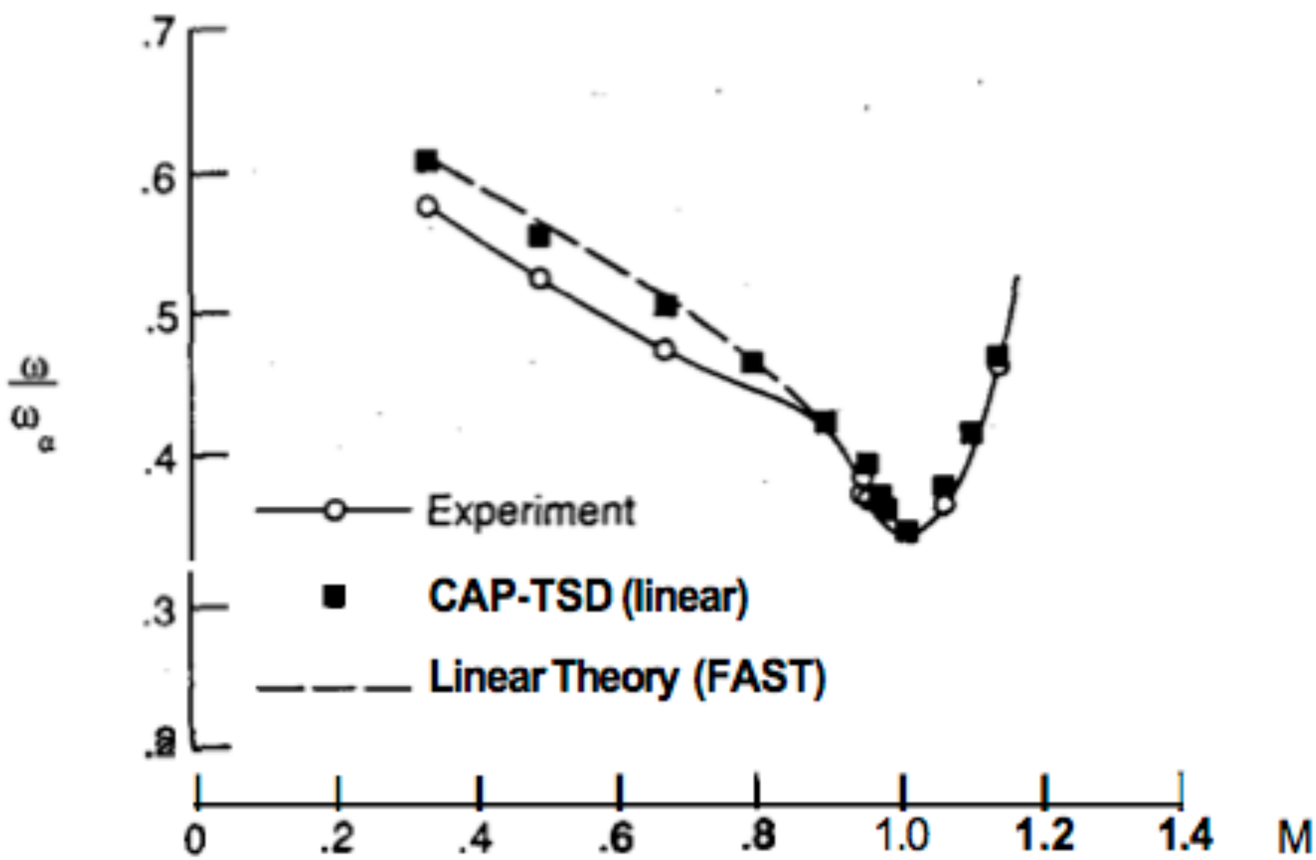
Early Results (1 of 2)

- "Modern Wing Flutter Analysis by Computational Fluids Dynamics Methods", H. J. Cunningham, J. T. Batina, and R. M. Bennett, Journal of Aircraft, Volume 25, No. 10, October 1988, pp 962-968.

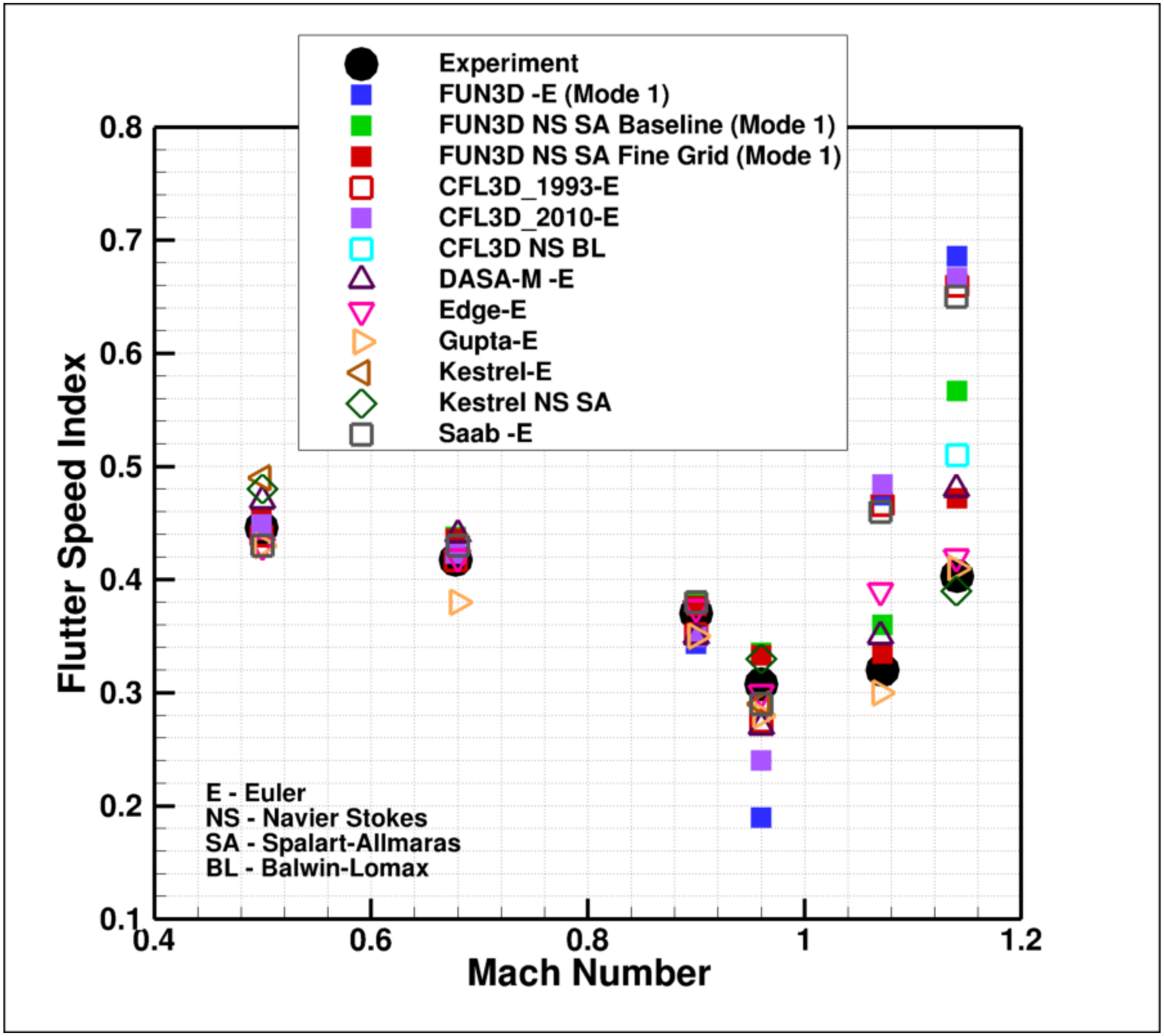


Early Results (2 of 2)

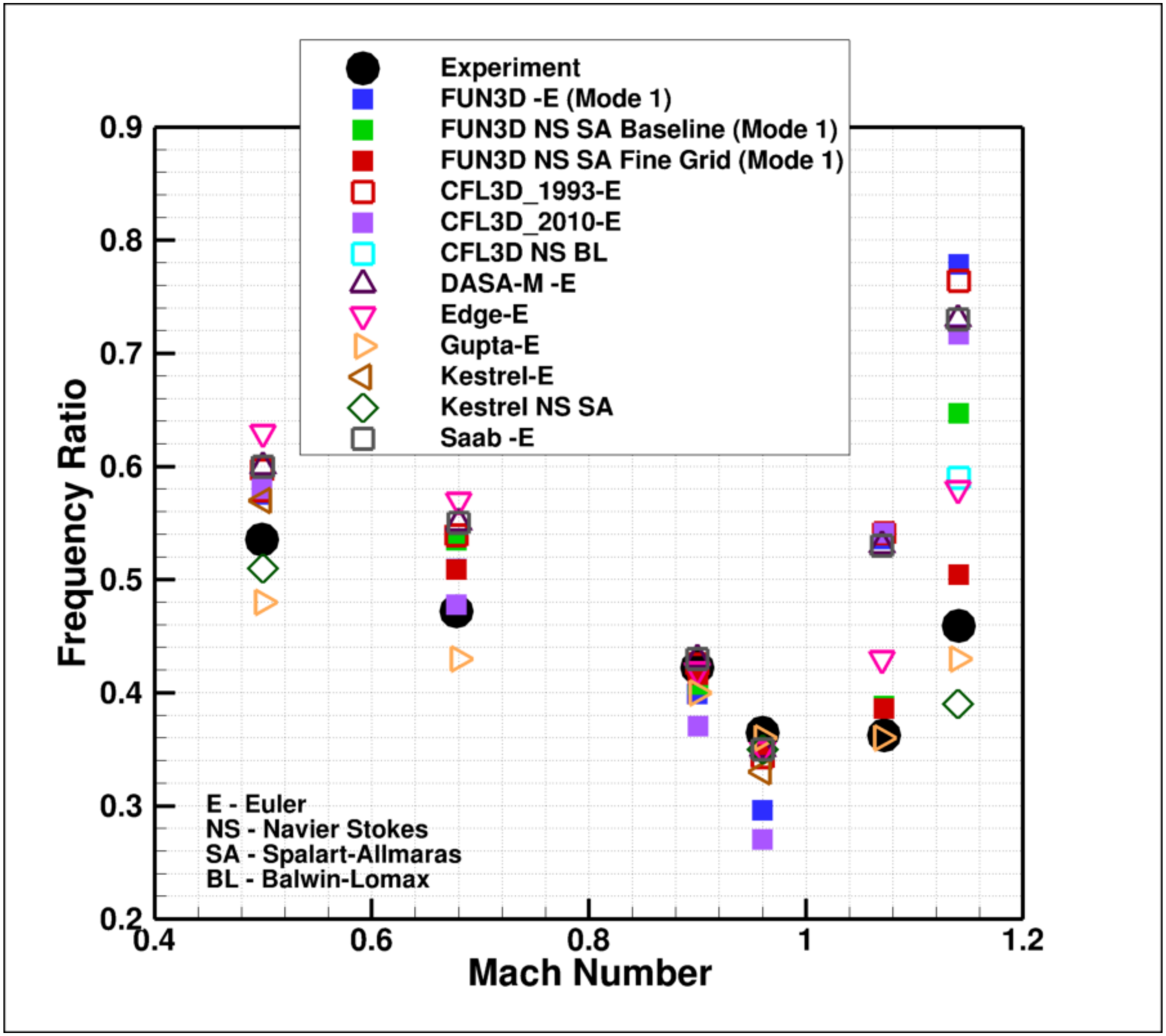
- “Modern Wing Flutter Analysis by Computational Fluids Dynamics Methods”, H. J. Cunningham, J. T. Batina, and R. M. Bennett, Journal of Aircraft, Volume 25, No. 10, October 1988, pp 962-968.



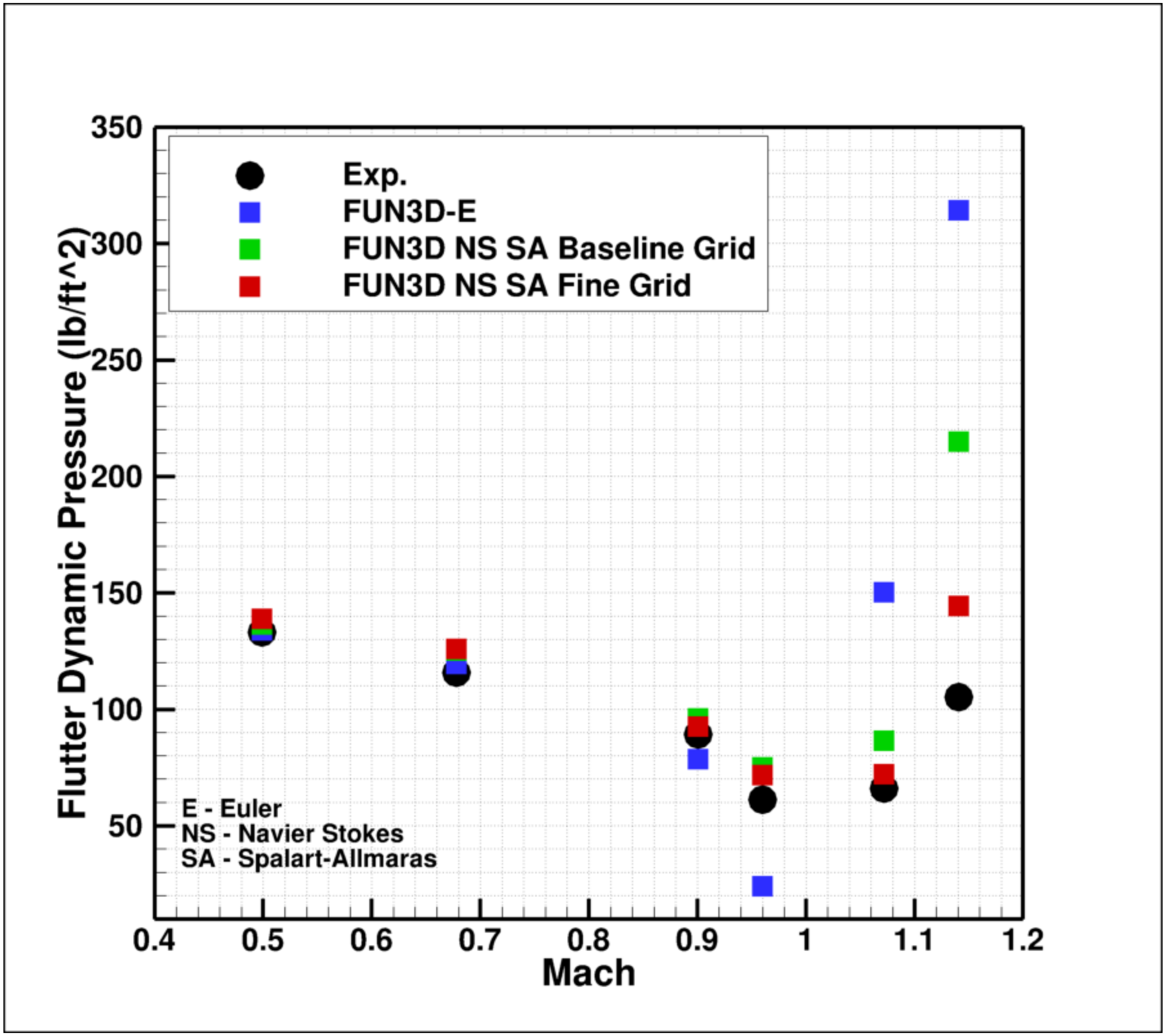
Published Results (Flutter Speed Index)



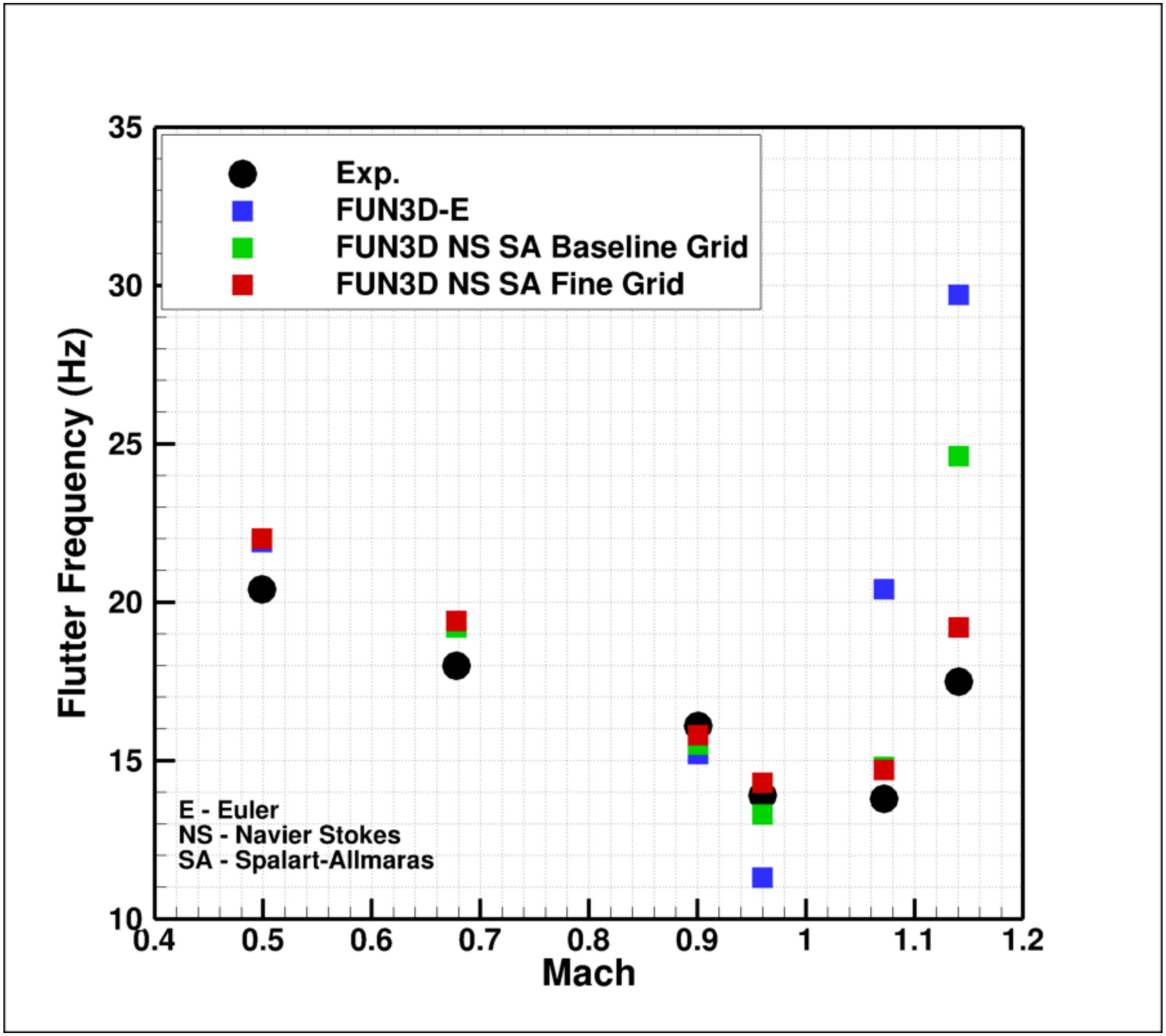
Published Results (Frequency Ratio)



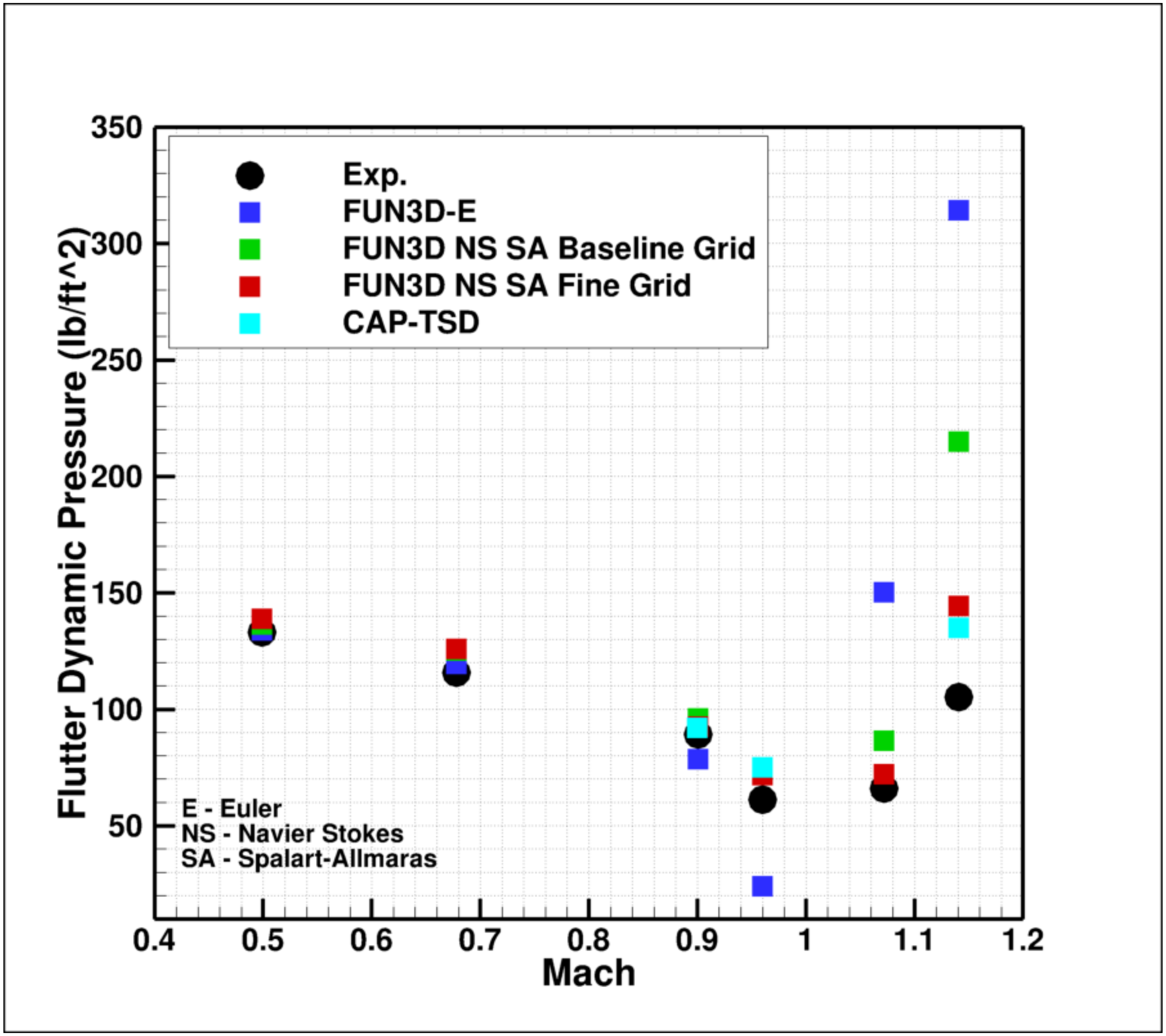
FUN3D Flutter Boundaries (Q, psf)



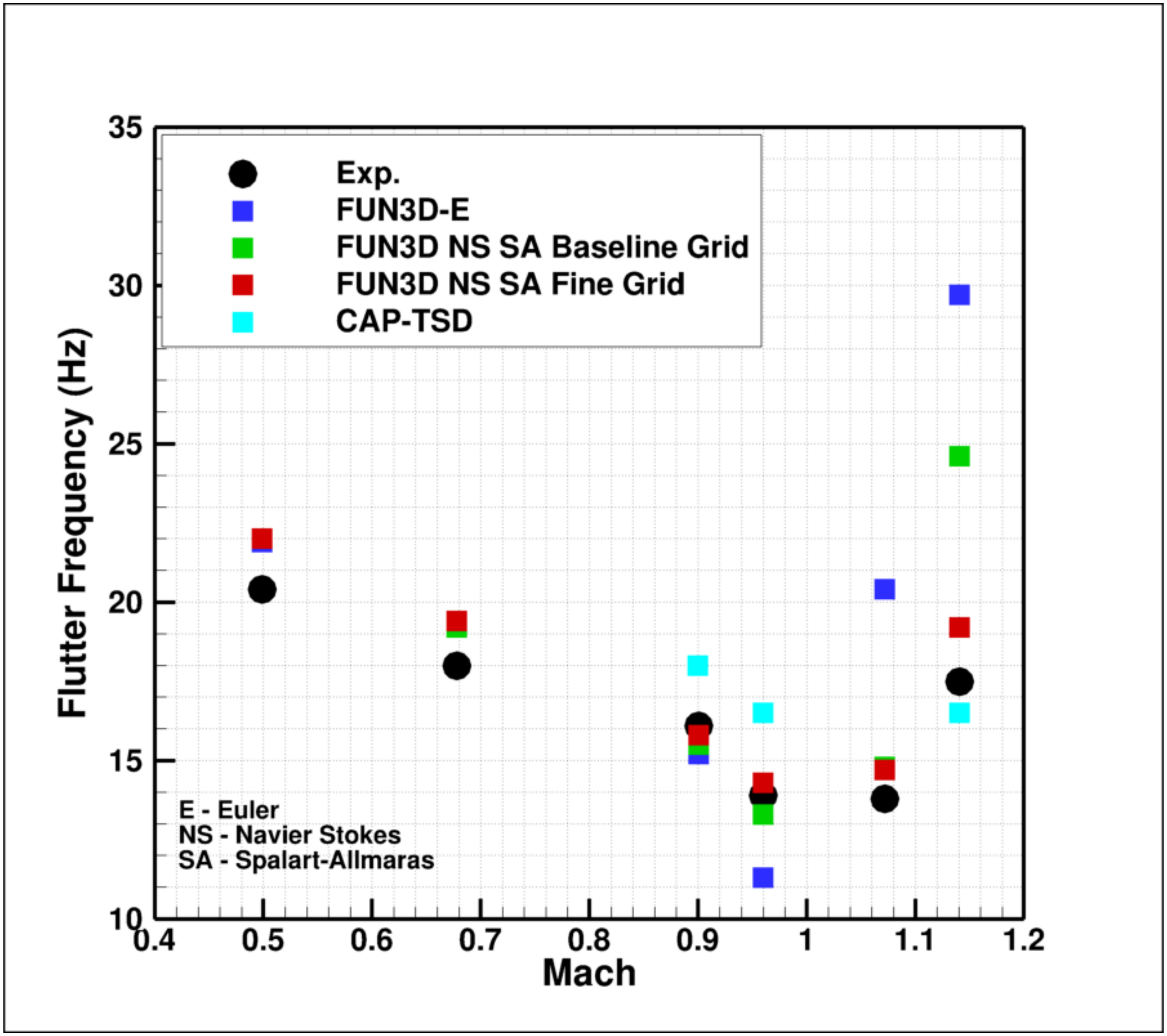
FUN3D Flutter Boundaries (f, Hz)



CAP-TSD (linear) Flutter Boundary (Q, psf)



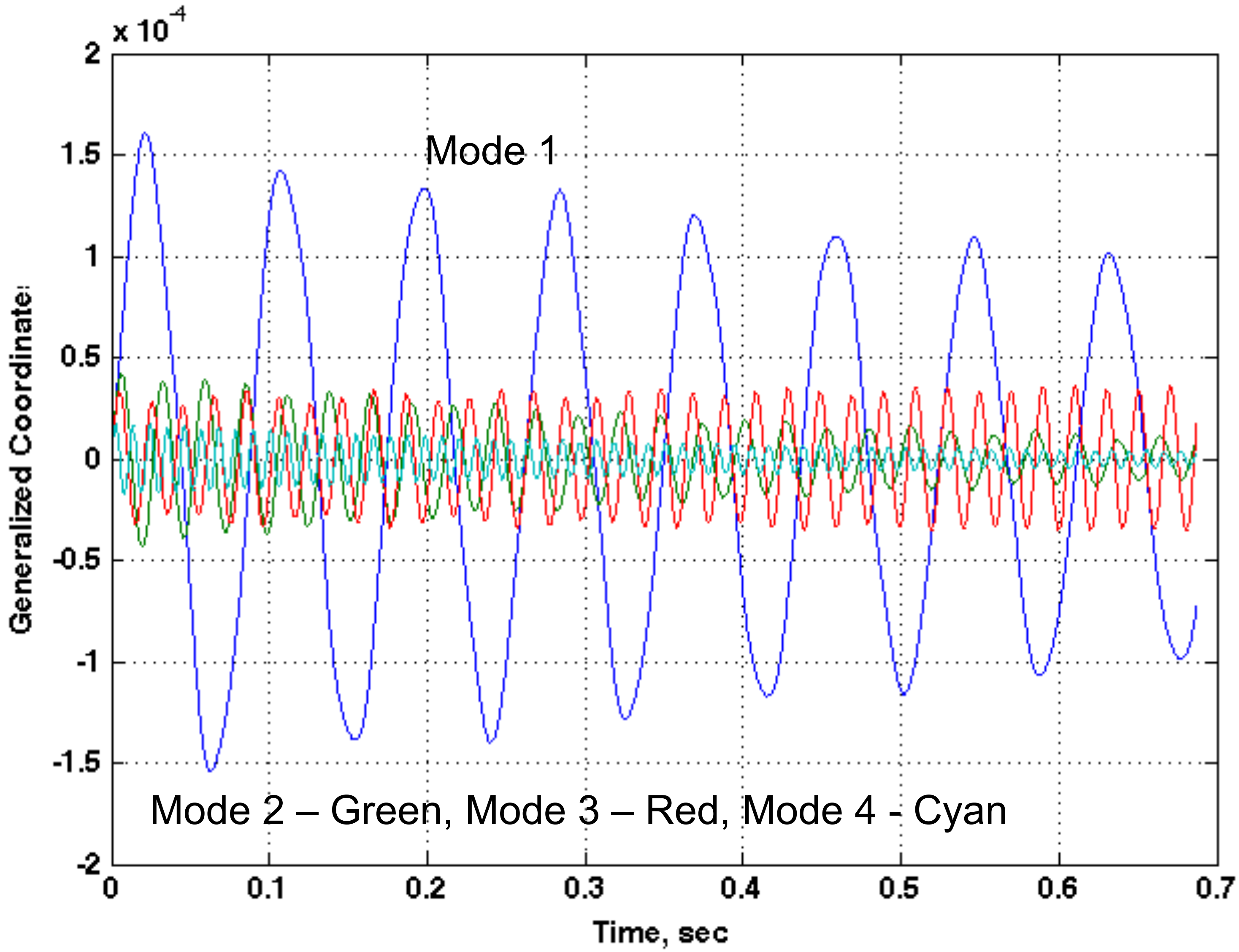
CAP-TSD (linear) Flutter Boundary (f, Hz)



So far…

- In mid-1980’s, Bennett et al computed the flutter boundary using kernel function aerodynamics (subsonic, supersonic) with good accuracy.
- Cunningham et al paper presented similar results using linear CAP-TSD.
- The AGARD 445.6 wing has a thin airfoil and is at zero degrees angle of attack, with a very narrow transonic region (around M=0.98).
- The flow before M=0.98 and shortly after M=1.00 is <u>linear.</u>
- The linear, inviscid, and viscous computations are consistent at subsonic conditions, as expected.
- The linear, inviscid, and viscous computations are NOT consistent at supersonic conditions.
- <u>Contrary</u> to several published references, the experimental flutter dip in dynamic pressure is NOT the result of highly nonlinear transonic flow (transonic flutter dip); compressibility is a primary cause for a “dip” in the flutter dynamic pressure with increasing Mach number (see Isogai).
- Some references have even stated that maybe the supersonic data is wrong. Irrespective of the data, the linear, inviscid, and viscous computations should be consistent in a linear region.
- BUT there is more…

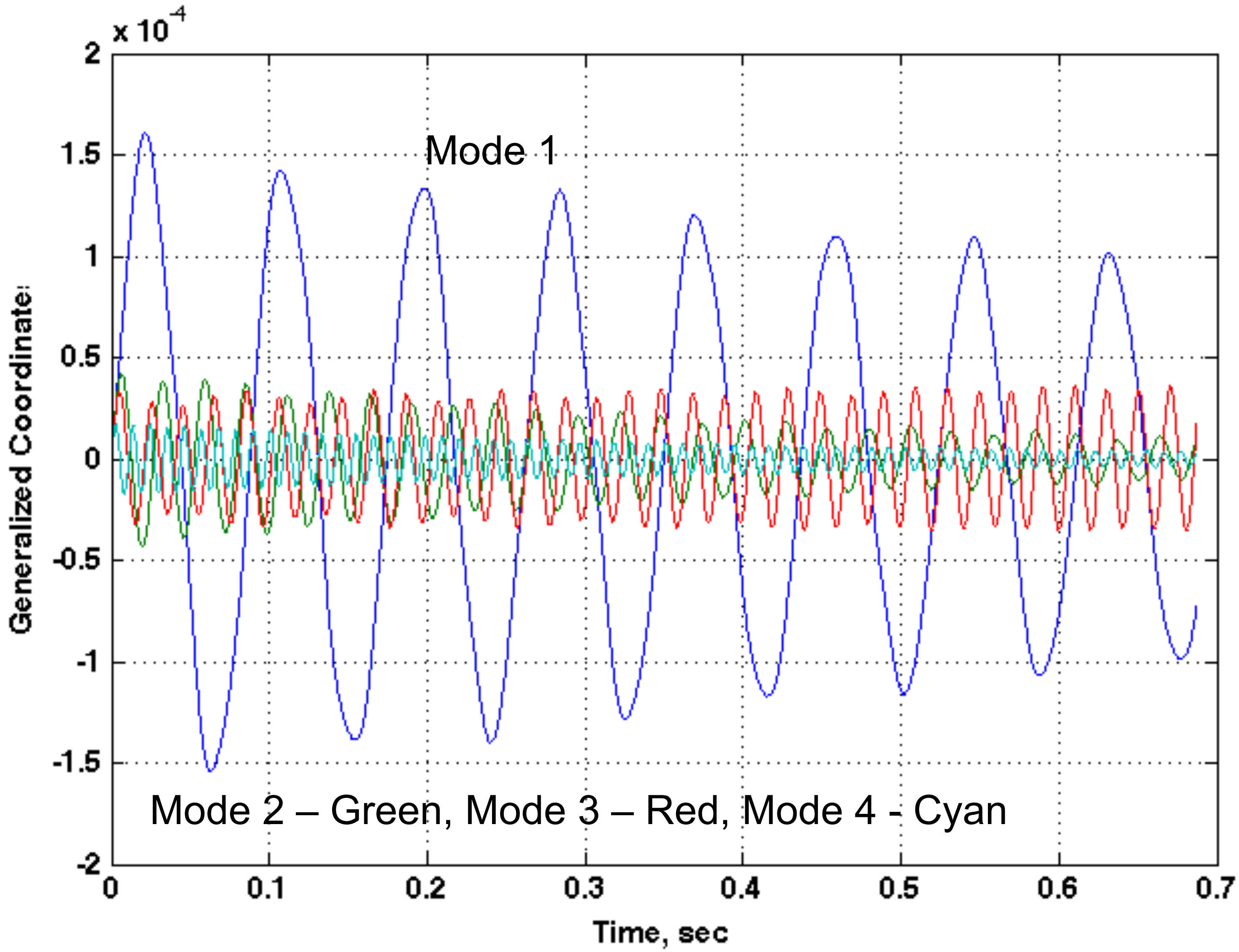
FUN3D, Euler, M=1.141, Q=30 psf, all modes



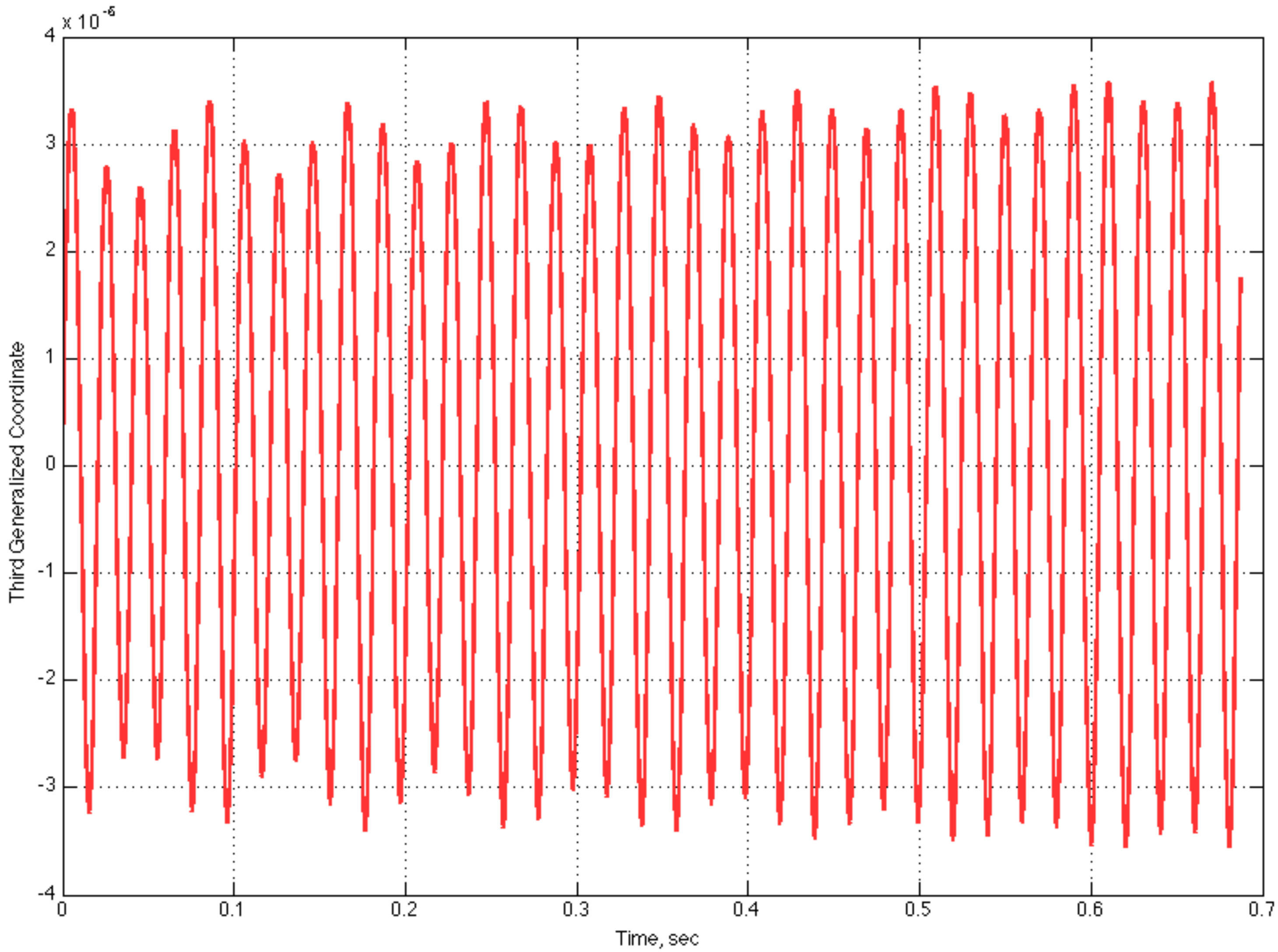
Post-Processing of AE Transients

- In the early days of computational AE, a great deal of effort was placed into proper post-processing of AE transients.
- It was well understood that to determine stability visually could be erroneous due to mixing of modal transients; that is, each modal response contains contributions from the other modes.
- However, the resultant transients were often not very long (reduce computational cost) which reduced the accuracy of any post-processing software.
- In addition, the focus tended to be on “visual inspection” in order to save time.
- Interesting point: Significant effort is placed on grid generation, significant effort is placed on accuracy of solution, minimal (if any) effort is placed on post-processing; defeats the purpose of all the work done to achieve an accurate solution.
- Hidden dangers: The effect of varying magnitudes of each modal response can result in an optical illusion if visual inspection is the only approach.
- Most post-processing algorithms have difficulty properly identifying unstable transients.
- The solution on the previous chart: stable or unstable? UNSTABLE

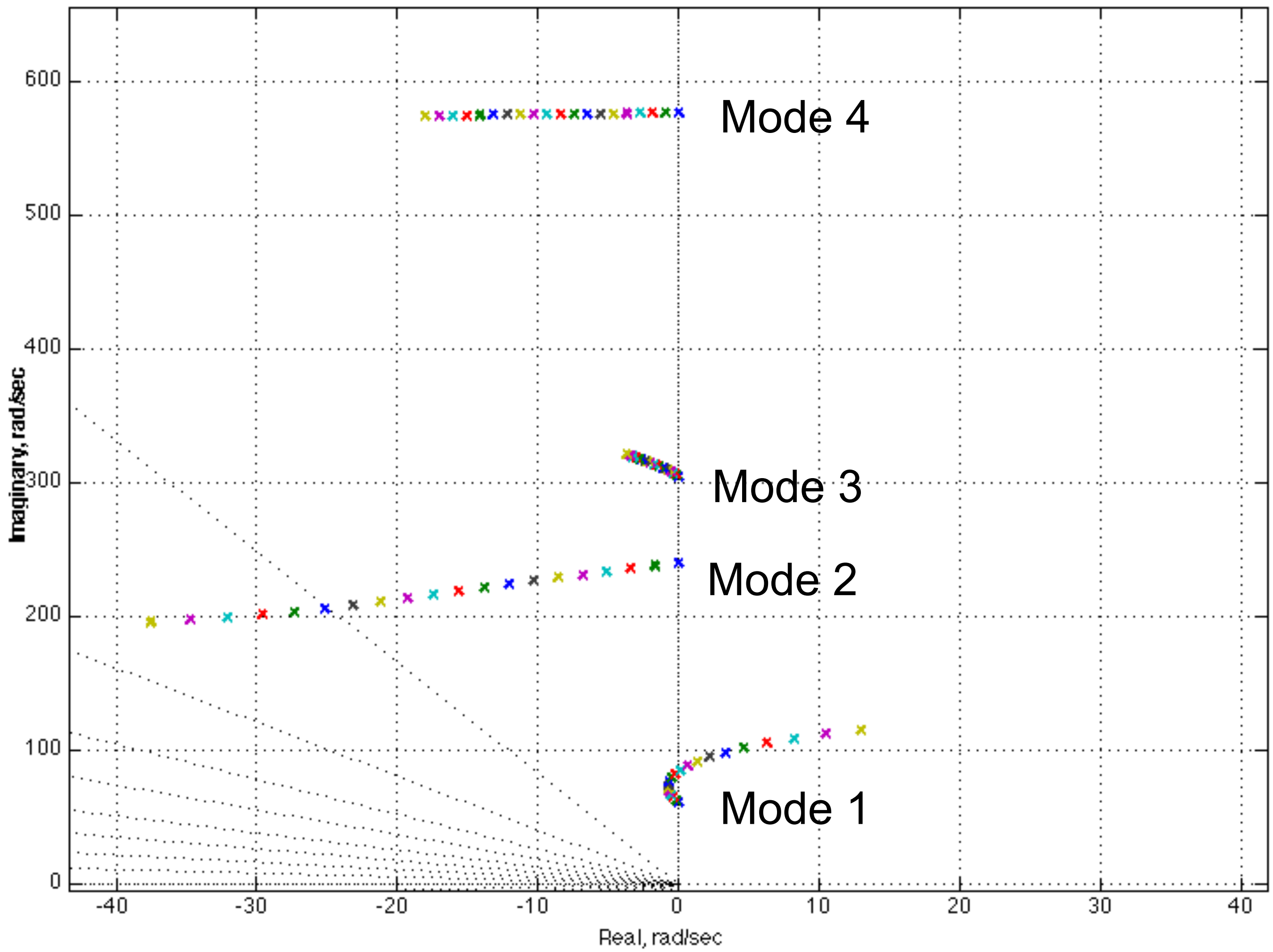
FUN3D, Euler, M=1.141, Q=30 psf, all modes



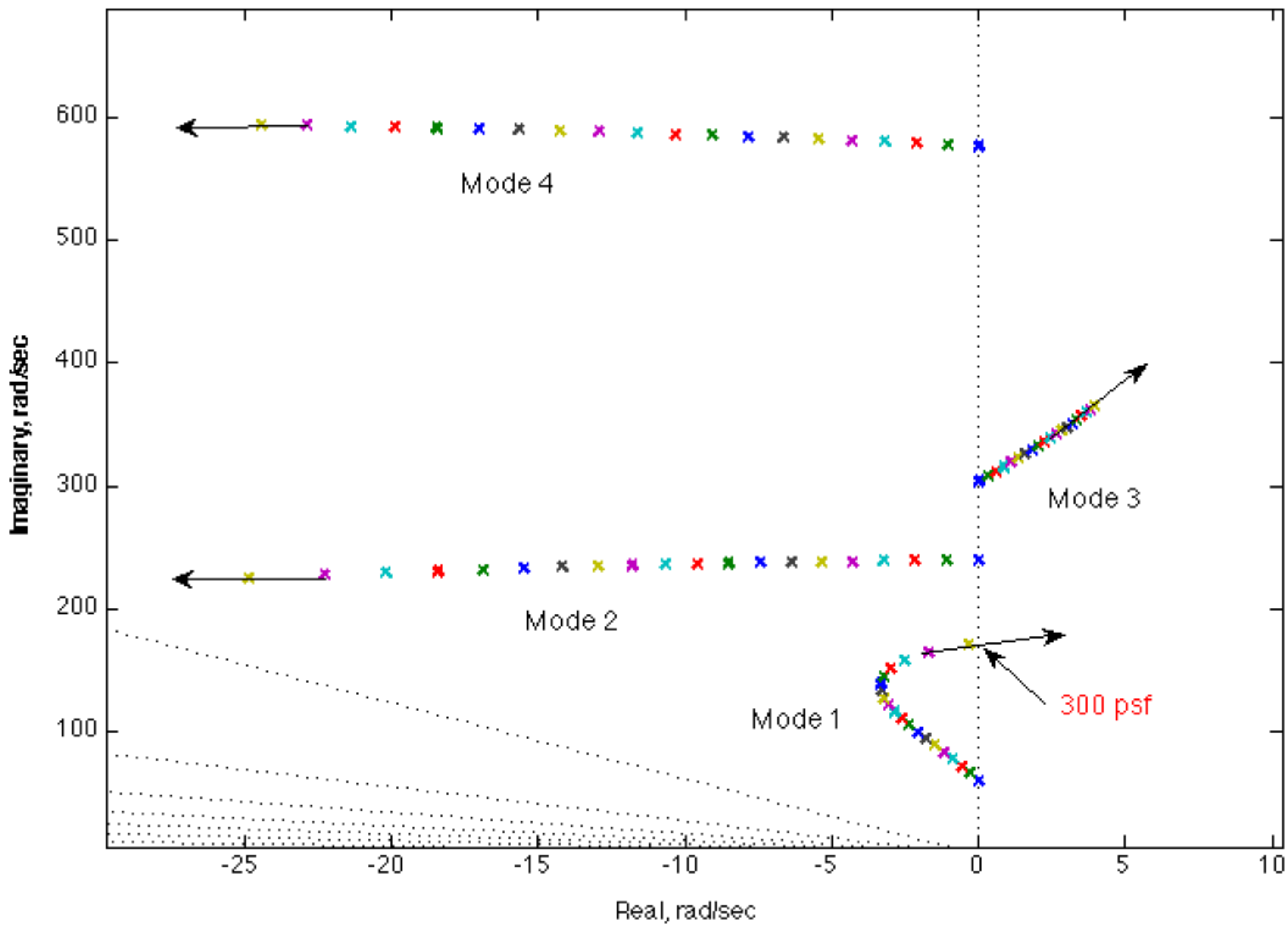
FUN3D, Euler, M=1.141, Q=30 psf, 3rd mode



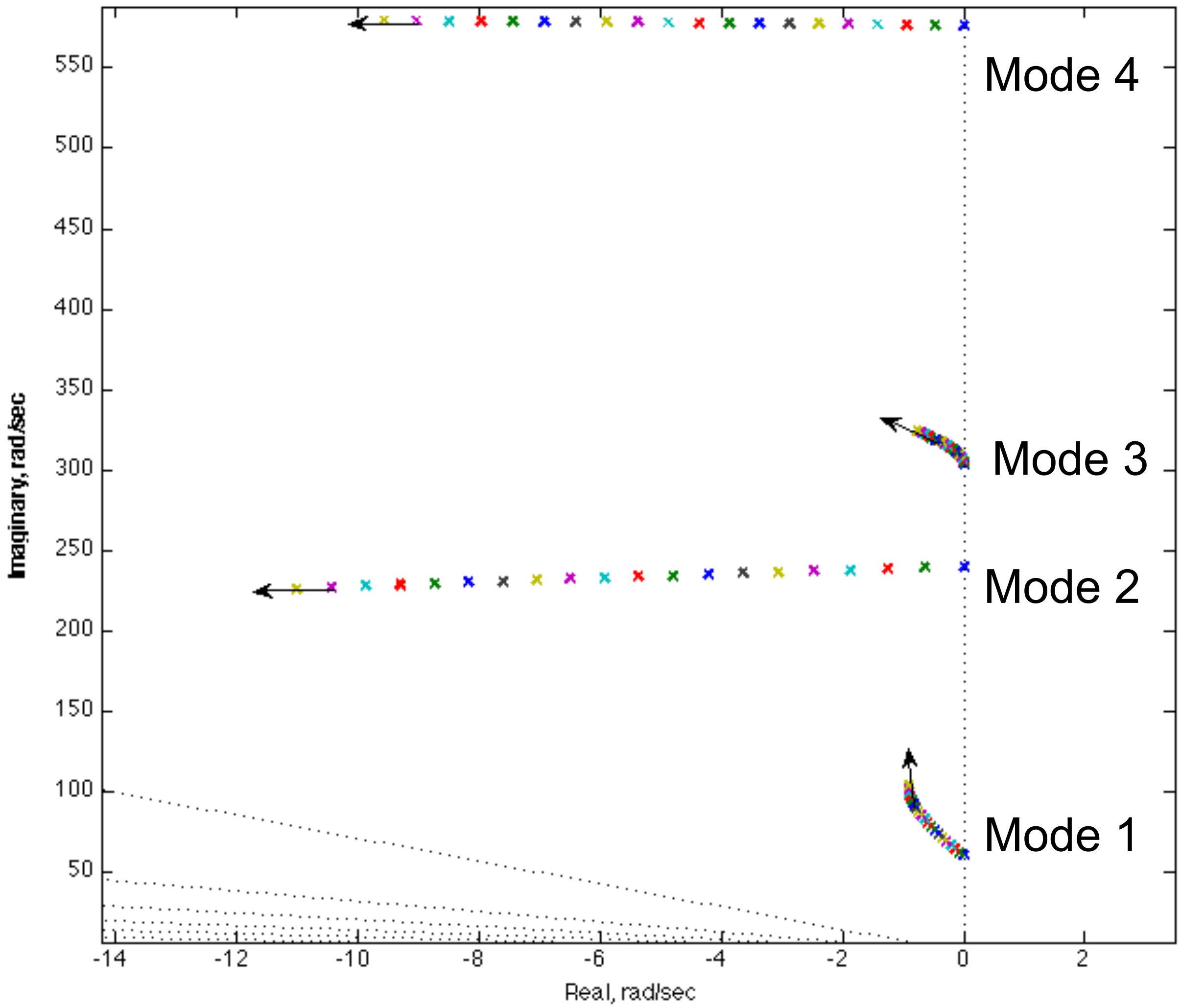
Root Locus (ROM), FUN3D, Euler, M=0.96



Root Locus (ROM), FUN3D, Euler, M=1.141

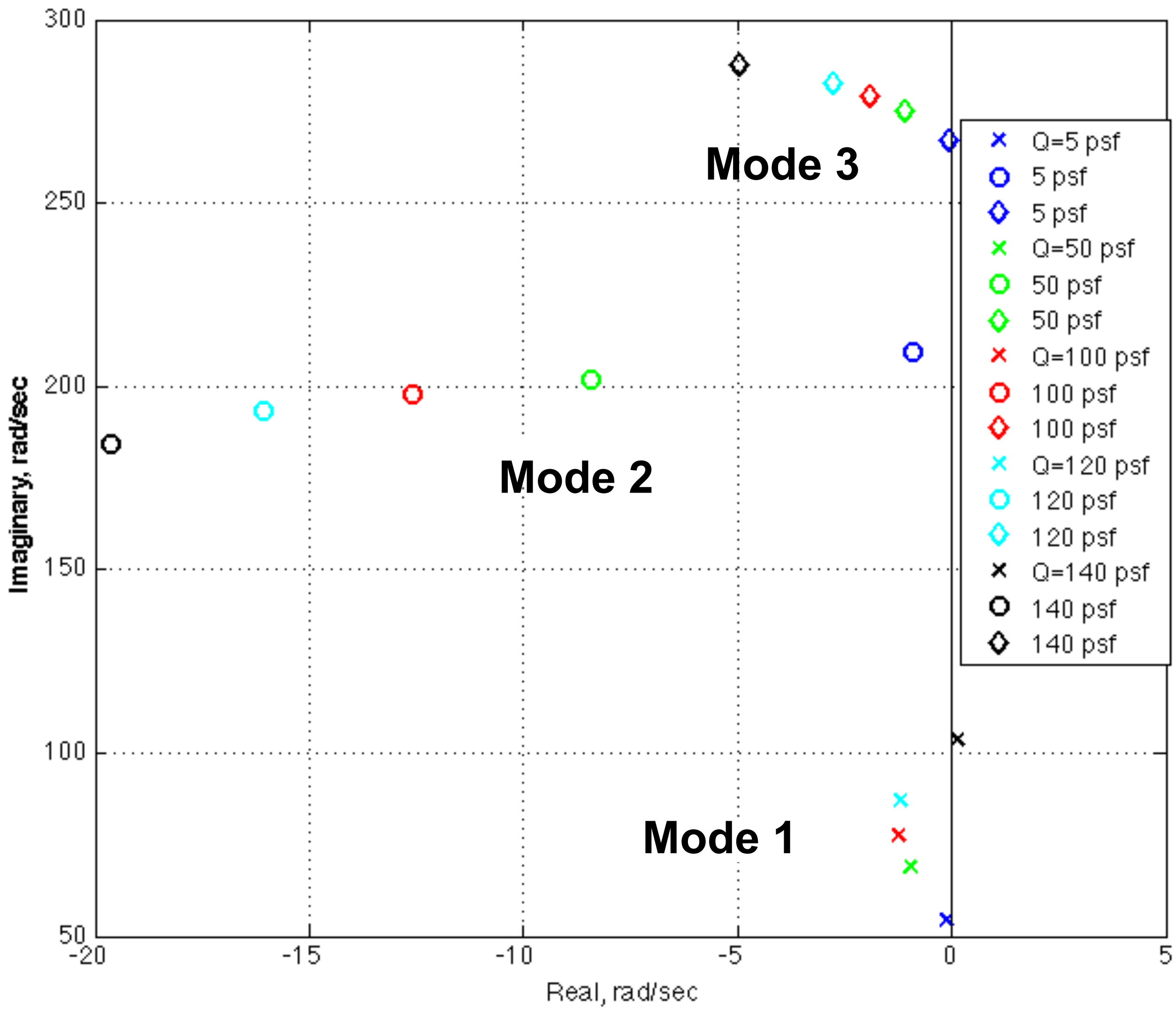


Root Locus (ROM), FUN3D, NS, M=1.141



Root Locus, CAP-TSD, Linear, M=1.141

DMPSIN



Concluding Remarks (1 of 2)

- Linear, inviscid, viscous, and ROM results were presented for the AGARD 445.6 wing at several Mach numbers.
- Linear, inviscid, viscous, and ROM results compare well to each other and to the experimental results at subsonic conditions.
- Inviscid and viscous results DO NOT compare well to each other nor the experimental results at supersonic conditions; but linear results DO compare well with experimental results at supersonic conditions.
- The AGARD 445.6 wing had a thin airfoil with a small transonic region, therefore most of its aeroelastic response should be linear.
- The dip in the experimental flutter boundary is caused by compressibility, not by nonlinear transonic effects.
- Inviscid (Euler) results indicate an unstable third mode not reported in the literature by other researchers.
- ROM root locus results reinforce the importance of root locus plots to view aeroelastic mechanisms.

Concluding Remarks (2 of 2)

- The purely visual inspection of AE transients is not dependable.
- The DAMPSIN code (Bennett et al, FORTRAN) has been revived in MATLAB (optimization).
- Summer student developed and performed studies on various post-processing techniques; a NASA TM is being prepared with the details.
- Important to re-iterate that the AGARD 445.6 wing flutter data is NOT a highly nonlinear flutter dataset.
- Maybe the focus of our analyses (for any configuration) should be the application of “right” fidelity, not necessarily “high” fidelity.
- The use of computational methods of <u>varying</u> fidelity yields an excellent opportunity for V&V as well as making some sense of what is physical and what is numerical.
- Clear need for the fabrication and re-testing of this “simple” configuration.

Walter.A.Silva@nasa.gov